6th Canadian Conf. Earthquake Engineering / Toronto / 1991 / 6ème Conf. Canadienne Sismique

Seismic liquefaction and flow deformations

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ABSTRACT

This paper presents a nonlinear finite element method for calculating the displacements in earth structures caused by seismic liquefaction. The method is used to evaluate post-liquefaction behaviour of Sardis Dam.

INTRODUCTION

One of the most challenging problems of seismic liquefaction is calculating the seismic response of earth structures which include zones of potentially liquefiable soils.

In current practice the post-liquefaction behaviour of an earth structure is assessed by means of static equilibrium analysis of the undeformed structure using the steady state or residual strength as the operating strength in the liquefied zones.

An alternative approach, more in keeping with the concept of designing dams for acceptable deformations proposed by Newmark (1965), is to evaluate the safety of the dam and the extent of necessary remedial measures on the basis of a tolerable amount of deformation for the low probability event specified by the design earthquake. The potential post-liquefaction deformations may be estimated using the computer program, TARA-3FL (Finn and Yogendrakumar, 1989), which is a specialized derivative of the general program TARA-3 by Finn et al. (1986).

STEADY STATE STRENGTH

The undrained steady state strength, S_{us}, is the crucial element controlling post-liquefaction deformations. There are two methods for

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obtaining S_{us}; laboratory tests on good quality samples from the field (Poulos et al., 1985), and from correlations between normalized standard penetration resistance $(N_1)60$ and S_{us} determined by analysis of liquefaction failures in the field (Seed, 1987; De Alba et al., 1987). Great uncertainties are associated with estimates in S_{us} by either method. The causes of uncertainty associated with these approaches have been discussed critically by Seed et al. (1988) and Finn (1989). Marcuson et al. (1990) also reviewed the problems associated with the above methods and concluded "the empirical correlation relating penetration resistance to field performance is adequate and may even be preferable to the testing of undisturbed samples". The most recent version of the Seed correlation is shown in Fig. 1.

STRUCTURE OF THE PROGRAM TARA-3FL

The basic theory of the finite element program TARA-3 has been reported by Finn (1985,1990) and Finn et al. (1989). So only procedures specific to TARA-3FL will be described here.

In a particular element in the soil structure, the shear stress-shear strain state which reflects pre-earthquake conditions is specified by a point P_0 on the stress-strain curve as shown in Fig. 2. When liquefaction is triggered, the strength will drop to the steady-state value. The post-liquefaction stress-strain curve cannot now sustain the pre-earthquake stress-strain condition and the unbalanced shear stresses are redistributed throughout the dam. In the liquefied elements, the stresses are adjusted according to the following equation,

$$d\tau = \frac{\partial f}{\partial \sigma'_m} d\sigma'_m + \frac{\partial f}{\partial \gamma} d\gamma \qquad (1)$$

where $\tau = f(\sigma'_m, \gamma)$. This process leads to progressive deformation of the dam until equilibrium is reached at the state represented by P_2.

Since the deformations may become large, it is necessary to update progressively the finite element mesh. Each calculation of incremental deformation is based on the current shape of the dam, not the initial shape as in conventional finite element analysis.

DEFORMATION ANALYSIS OF SARDIS DAM, MISSISSIPPI

Preliminary deformation studies of Sardis Dam have been conducted using TARA-3FL for various assumptions about the magnitudes and distributions of the residual strengths in the liquefied zones. Evaluations of dam performance during seismic shaking and potential remedial measures are still underway, so final results cannot be presented here. Instead some results are presented to show the type of information provided to the design engineer by deformation analyses.

The general configuration of the Sardis Dam is shown in Fig. 3. During the design earthquake, liquefaction is predicted to occur in the core and in a thin seam of clayey silt or silty clay in the top stratum clay in the foundation. The thin layer may be seen clearly in Fig. 4. The liquefaction potential of the sands and silts was evaluated using Seed's liquefaction assessment chart (Seed et al., 1985) and the Chinese criteria for soils with plastic fines by Wang (1979).

The residual strength (steady state strength) in the core was assumed to be 5 kPa (100 psf) based on Seed's correlation between corrected standard penetration resistance $(N_1)_{60}$ and residual strength shown in Fig. 1 (Seed and Harder, 1990). From a variety of studies, the residual strength in the thin layer in the foundation was assumed to be $S_r = 0.075\ \sigma'_{vo}$ (Woodward Clyde Consultants, 1989). The original strength of the thin layer was taken as 100 kPa (2000 psf).

The large differences between the initial and post-liquefaction strengths in Sardis Dam resulted in major load shedding from liquefied elements. This put heavy demands on the ability of the program to track accurately what was happening and on the stability of the algorithms. Therefore it was imperative to have an independent check that the computed final deformed positions were indeed equilibrium positions. The most direct check is to run a conventional stability analysis on the deformed position. If the major deformations occur during the earthquake, the resulting factor of safety should be greater than unity because some of the deformation field is driven by the inertia forces. If the major deformations occur relatively slowly after the earthquake, the factor of safety should be close to unity.

In one analysis of Sardis Dam, the residual strength values specified above were used, but assuming a minimum value of 17.5 kPa (350 psf) in the thin liquefied layer in the foundation. The initial and final deformed shapes of the dam for this case are shown in Fig. 4. Very substantial vertical and horizontal deformations may be noted, together with intense shear straining in the weak thin layer. The static stability of the deformed shape was analyzed using the program UTEXAS2 (USACE, 1989). This program uses Spencer's method (1973) which satisfies both moment and force equilibrium. The factor of safety was found to be close to 1.0. It is also interesting to note that the critical slip surface for UTEXAS2 analysis exited the slope near the location suggested by the finite element analysis using TARA-3FL.

The reliability of TARA-3FL in predicting stable deformed shapes was tested by parametric studies with various assumptions about the steady state strength in the thin liquefiable layer. The factors of safety of the undeformed and deformed dam cross-sections were determined using UTEXAS2. The factors of safety for the undeformed dam are given by the solid sloping line in Fig. 5. The points give the factors of safety of the post-liquefaction deformed sections. The steady state strengths in Fig. 5 represent either a constant value for the layer or an imposed minimum value when $S_{us} = 0.075\ \sigma'_{vo}$. In the clearly unstable region defined by a factor of safety less than one for the undeformed section, the computed factors of safety for the deformed sections were in the range of 1 ± 0.05. This is the theoretical error band associated with UTEXAS2. Many results of this type, for different assumptions about the residual strengths, suggest that the TARA-3FL analysis does indeed achieve equilibrium positions even for large drops in strength due to liquefaction.

Studies were made of the sensitivity of displacements to various levels of residual strength in the thin layer. The variations in the vertical displacements at the upstream edge of the crest (curve 1) and in the horizontal deformations at the midpoint of the upstream slope (curve 2) are shown for various levels of constant residual strength in the thin liquefied layer in the foundation in Fig. 6. The increase in displacement is gradual with decrease in residual strength until the strength drops to about 20 kPa (400 psf) when the displacements begin to increase very rapidly. The variation in vertical displacements (curve 3) is also shown in Fig. 6, for residual strengths $S_r = 0.075\ \sigma'_{vo}$. For variable minimum residual strengths, the displacements increase rapidly when the minimum strength is about 15 kPa (300 psf). This information is critically important when choosing an appropriate residual strength for design purposes from the usually very scattered residual strength data derived from laboratory tests or from field penetration test data.

It is also possible to determine the loss in freeboard associated with various factors of safety based on the original configuration of the dam for various residual strengths. The variation of vertical crest displacement (loss of freeboard) with factors of safety of the undeformed dam are shown for various values of residual strength in Fig. 7. For the first time a designer has available the deformation fields associated with different factors of safety for a particular dam. This information is helpful in interpreting the implications of a given factor of safety.

CONCLUSIONS

Deformation analysis of earth structures with liquefied zones using TARA-3FL is a very useful complement to conventional slope stability analysis for studying the effects of liquefaction and designing remedial measures. It provides the designer with additional useful information which assists him in exercising his judgement effectively. It is particularly useful when only partial remedial measures are employed and liquefaction is still permitted to occur in other sections of the structure. In these cases not only the global stability guaranteed by conventional stability analysis is important but also the localized displacements that occur in the liquefied sections.

TARA-3FL analysis also permits magnitudes of crucial deformations such as crest subsidence to be associated with factors of safety of the undeformed structure. This capability provides an essential link between current design practice and the proposed new procedure based on tolerable deformations.

ACKNOWLEDGEMENTS

Initial development of TARA-3FL was supported by Sato-Kogyo Co., Tokyo, Japan. Later developments were funded by the National Science and

Engineering Council of Canada under Grant No. 81948. Permission by Chief of Engineers, U.S. Army Corps of Engineers to present data from the Sardis Dam study is gratefully acknowledged.

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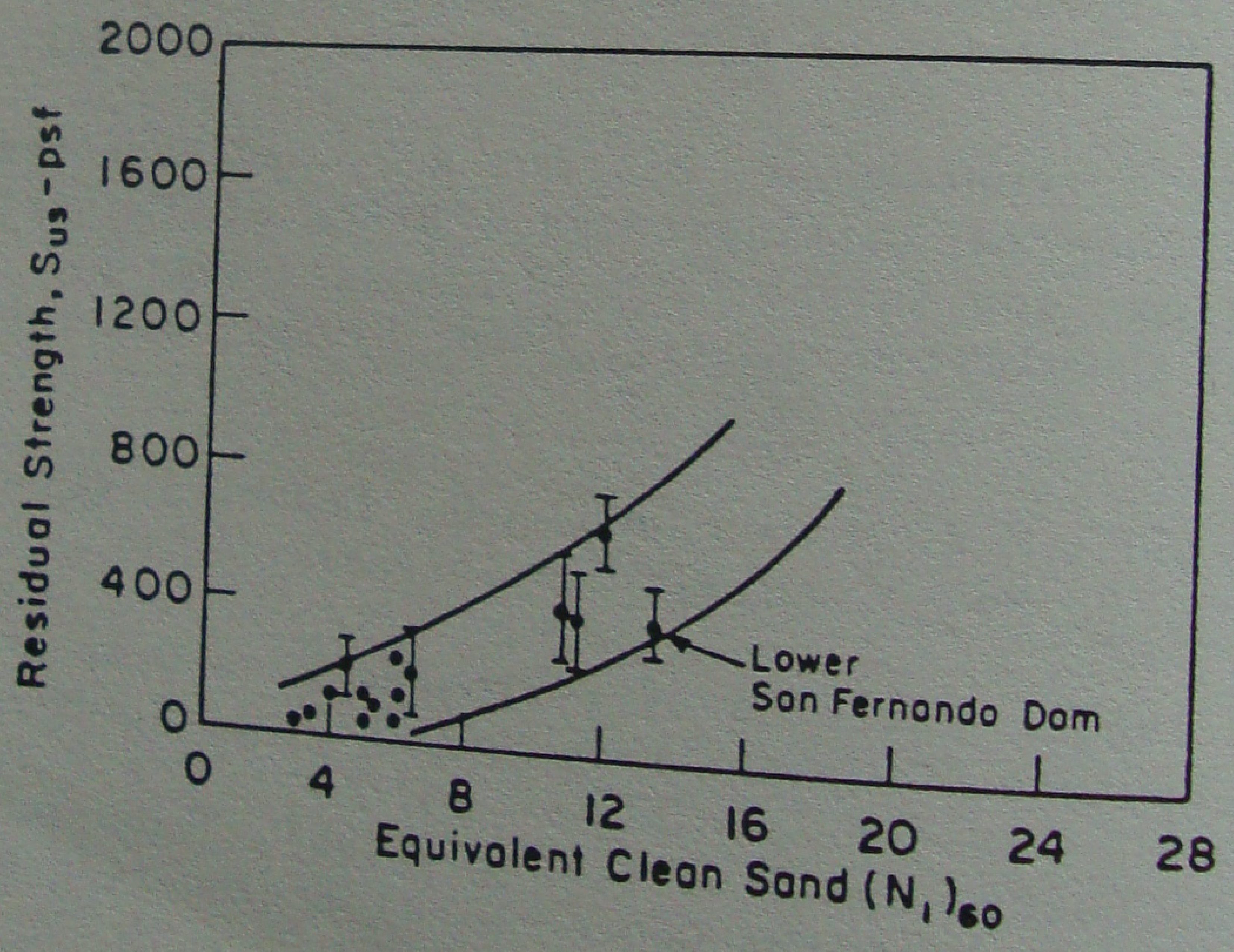

Figure 1. Tentative Relationship Between Residual Strength and Standardized SPT N Values for Sands (Seed et al., 1988).

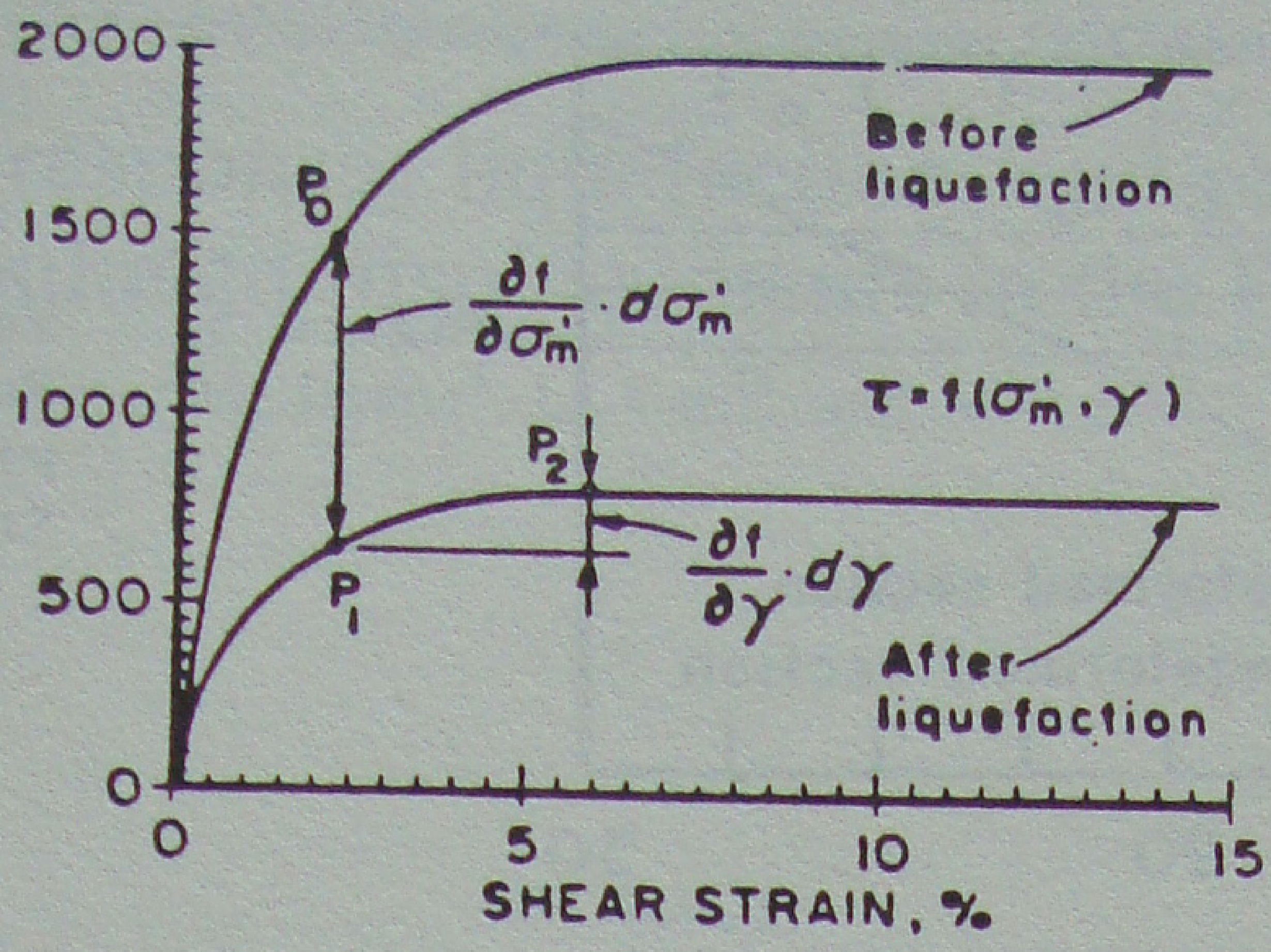

Figure 2. Adjusting Stress-Strain State to Post-Liquefaction Conditions.

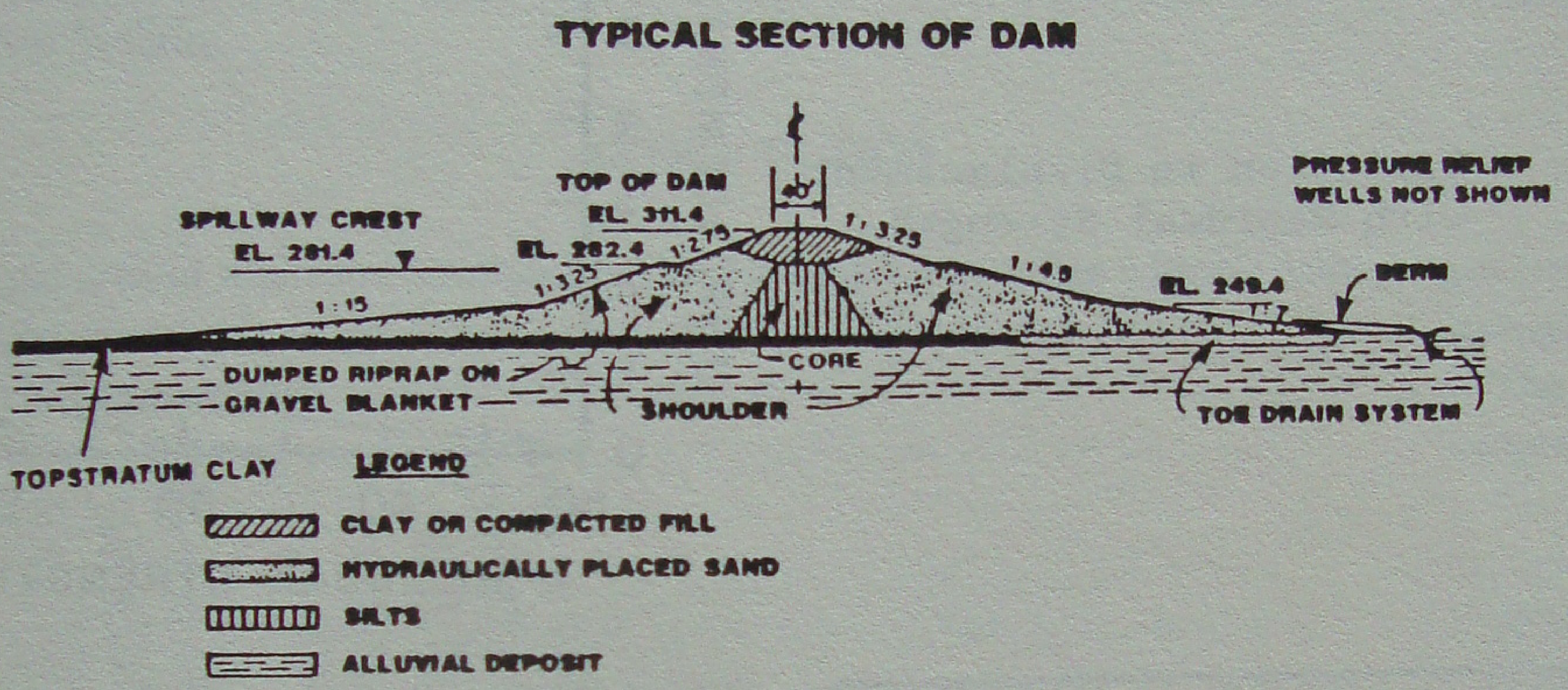

Figure 3. Typical Section of Sardis Dam.

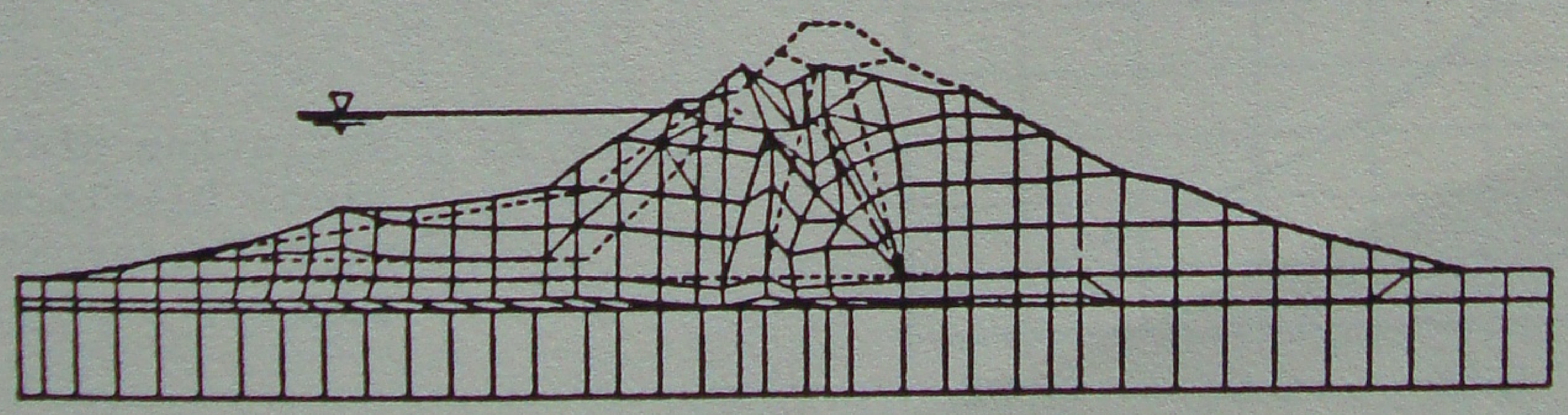

Figure 4. Initial and Post-Liquefaction Configurations of Sardis Dam.

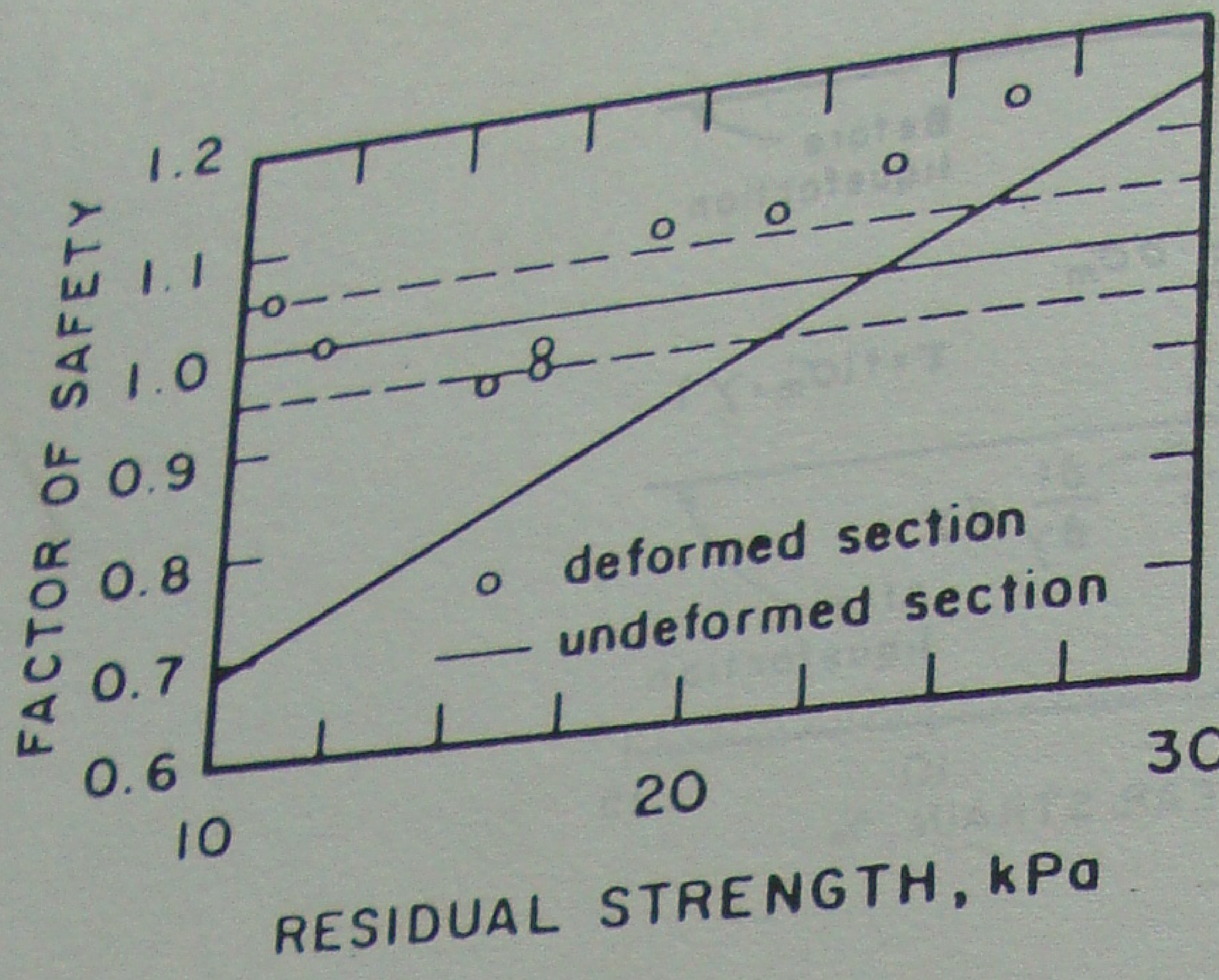

Figure 5. Variations in the Factor of Safety with Residual Strength.

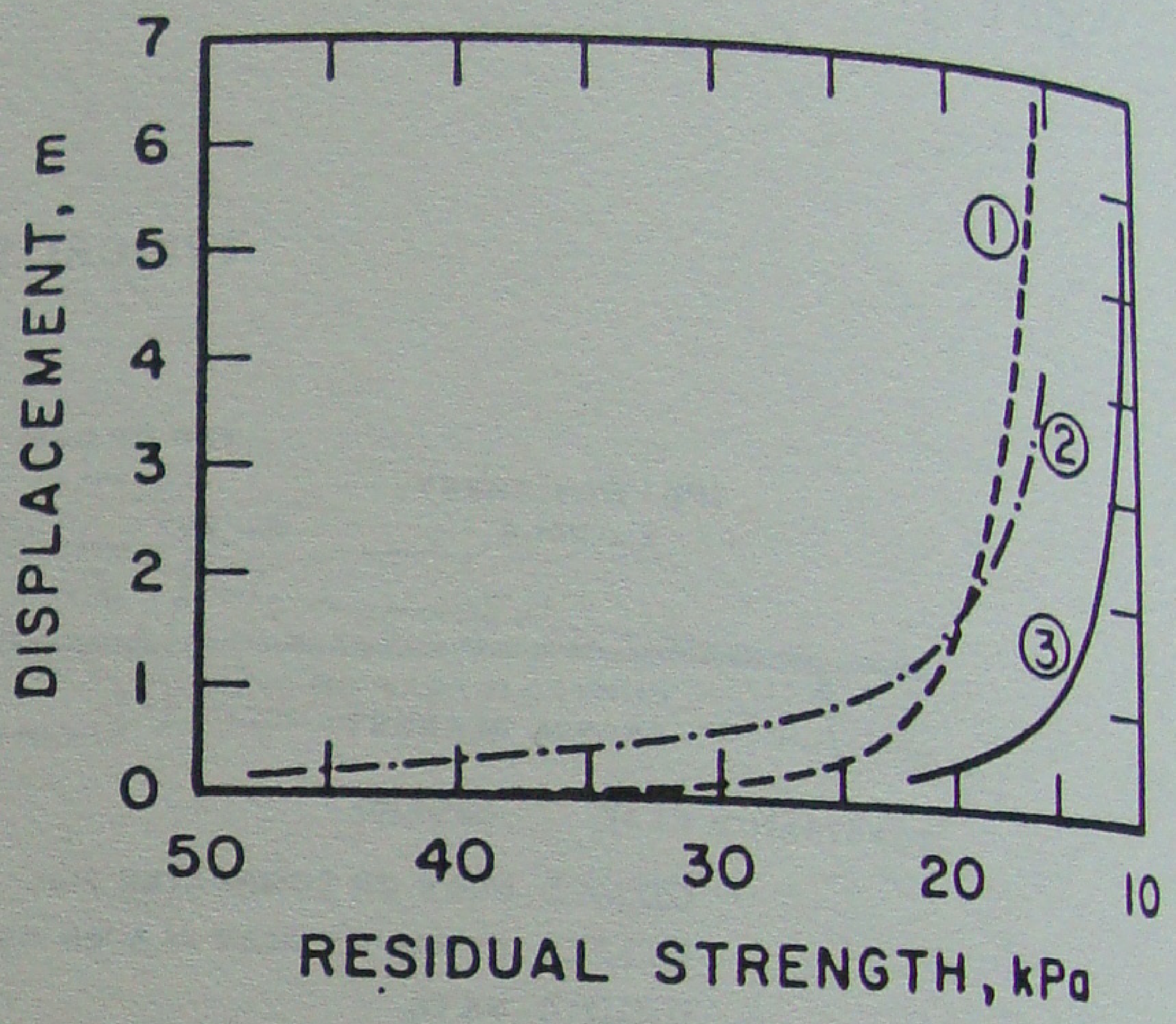

Figure 6. Variation in Displacement with Residual Strength

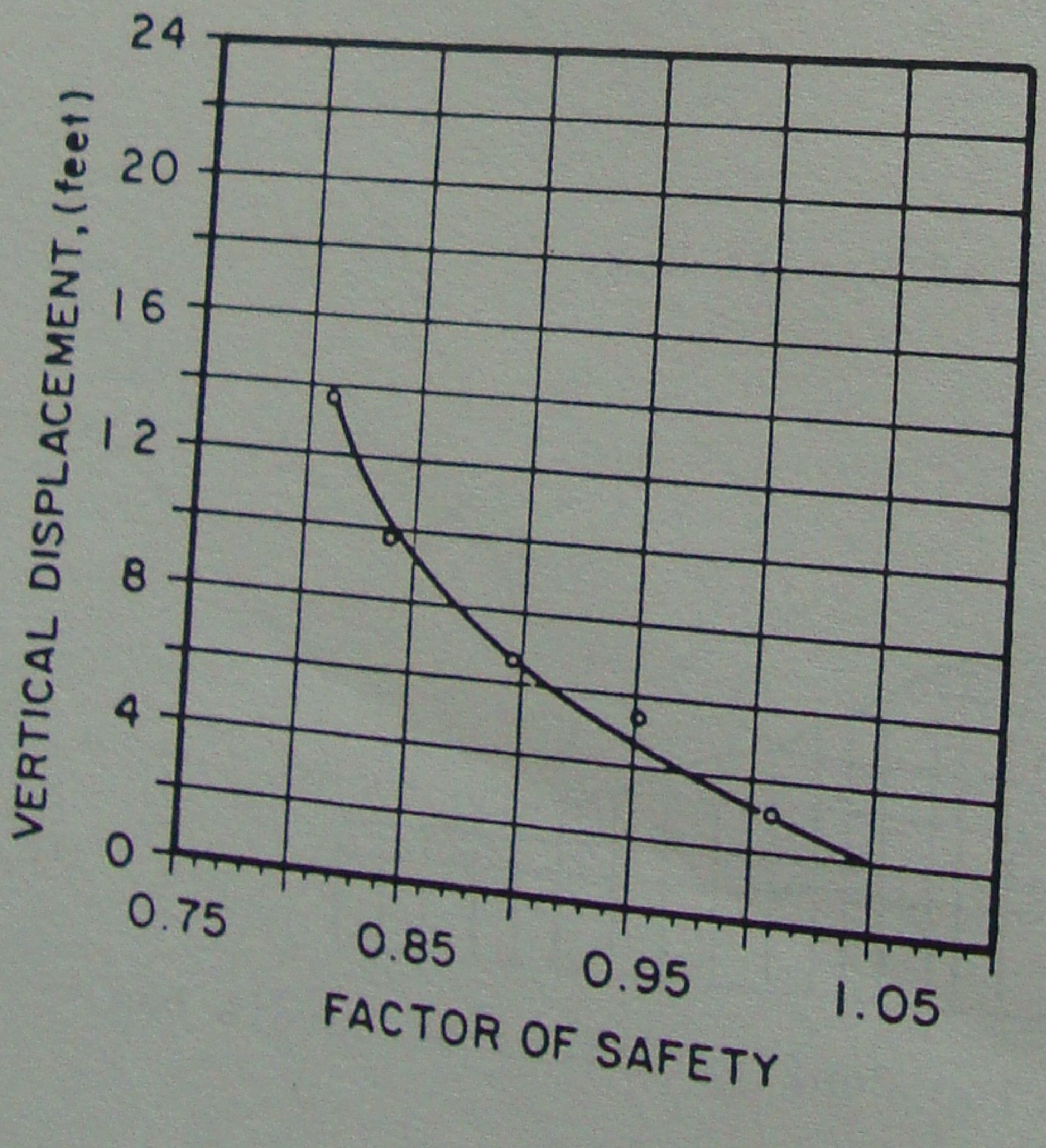

Figure 7. Variation of Vertical Displacement with Factor of Safety.